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Studies of Victorian Seismicity

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Abstract: One hundred and seventy-five earthquakes have been instrumentally located in Victoria in the years 1958-1966 inclusive, and analysed for their geographic and time distribution, recurrence relationship, strain release, and direction of motion characteristics. Before November 1964, the strain release was logarithmically dependent on time, but after this date, it has been linear with time and there has been an unusual number of shocks of magnitude 4 or greater. A preliminary catalogue of earthquakes felt in Victoria confirms that the eastern half of the State has more earthquakes than the west, and that there are three principal active zones.

INTRODUCTION

Earthquakes are not uncommonly felt in Victoria, although the frequency and the size of shocks are minor compared to the active regions of the world. But, as recognized by Jaeger and Browne (1958), the very scarcity of shocks can be an advantage because it allows the pattern of seismicity to be observed rather clearly.

Although a number of authors have written about individual notable shocks or the distribution of shocks (Gregory 1903, 1910; Holmes 1933; Gaskin 1947; Burke-Gaffney 1951), it is only since 1958-1959 that better instrumental coverage has allowed detailed studies of Victorian earthquakes to be made.

The results of these studies, up to the end of 1966, are presented here. Consistent patterns of earthquake occurrence can be discerned even in this small time span. Continuing studies are required for verification, to observe new and more subtle patterns, and to provide data for the assessment of earthquake hazards in Victoria.

A CATALOGUE OF VICTORIAN EARTHQUAKES

A catalogue of over 280 earthquakes felt in Victoria since the commencement of settlement is presented in Table 1.

The primary source of most of these data is a collection of manuscript books and clipping books compiled by the staff of the Victorian Government Astronomer, and at present held by the Melbourne Observatory Group of the Bureau of Mineral Resources. Where possible, checks from other sources have been made, and details of the references are included in the Appendix to this paper. The intensities have been assigned by the writer from the descriptions in the various sources, using the 1956 version Modified Mercalli Scale (Richter 1958).

The catalogue is not complete, for two main reasons. First, by no means all the printed sources have been examined. Diligent searching of the files of country newspapers, and of regional histories and their sources would no doubt reveal additional details of many shocks, and perhaps allow more confident assessment of intensities. Second, not all the earthquakes felt in Victoria would have been reported. From the commencement of settlement in 1835 until about 1883, only six shocks were reported, but the attention of the Government Astronomer seems first to have been drawn to seismology by the extraordinary swarm of earthquakes in 1883-1884 and 1885. A number of these were felt in coastal Victoria, and some in Melbourne. Lighthouse keepers at Gabo Island and elsewhere were recruited to report the tremors they felt, and all reports were carefully entered at the Observatory. Interest continued until about 1914, but declined after that until about 1932 when Holmes (1933) worked out an epicentre for the Mornington earthquake of that year. Since then, there has been a tendency to work from instrumental locations, and to collect felt reports only incidentally.

The number of catalogued earthquakes occurring in one degree 'squares' has been plotted in Fig. 1. As locations are only approximate, this coarse spacing is all that is warranted. When a report is from a locality near a boundary, a fractional count has been allotted to adjacent squares. The numbers ringed, and with an arrow, at east

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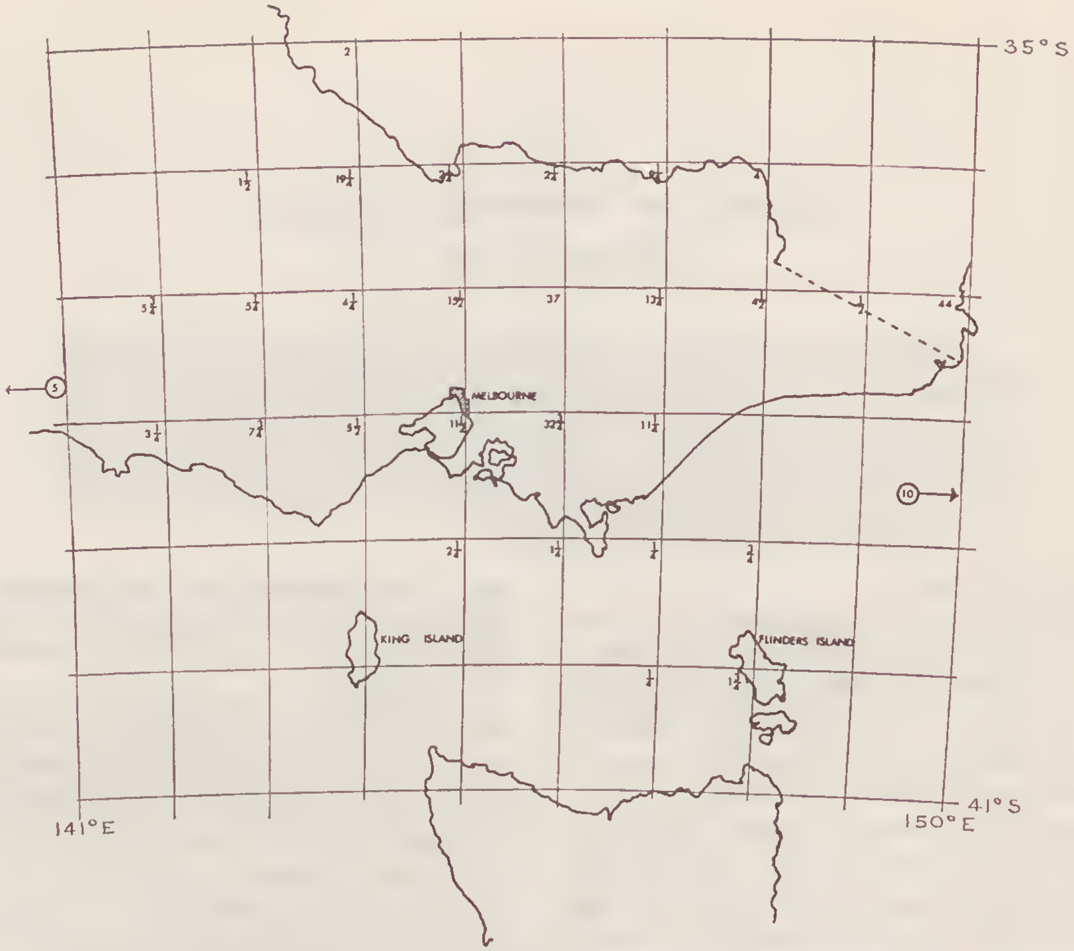

FIG. 1—Historical seismicity of Victoria. The numbers are the total of felt earthquakes from Table 1 which appear to have had their epicentres in the one degree 'squares'.

and west, show the number of shocks originating beyond the boundaries of the area, which were felt in Victoria. No attempt has been made to include Tasmanian earthquakes.

The most obvious feature of the diagram is the concentration of shocks round Melbourne, which is mainly but not entirely a reflection of the centralization of Victorian population. Next, it may be remarked that more shocks are reported from east of Melbourne than from the west. This is despite the scarcity of population in the Eastern Highlands and reflects the more active tectonic regime to the east. But there are persistent reports of earthquakes in the area centred on Wedderburn in the northwest. The large number of shocks reported from the far east of the State is due to the reports from the Gabo Island lightkeeper of the 1883 swarm.

The count omits a number of aftershocks, because it is usual to find only a general comment that there were 'several aftershocks' in the reports. This omission probably helps to preserve the real pattern of seismicity.

EARTHQUAKES IN VICTORIA 1959-1966

In 1956-1958, new instruments well adapted to local earthquake recording were installed in Melbourne, Canberra, and in the Snowy Mountains. In the course of the routine work of the Geophysics Department of the Australian National University (ANU) using these stations, a number of earthquakes were located in Victoria, and to investigate the seismicity in more detail, the ANU commissioned new stations at Bogong in 1963, and at Buchan and Mt Tassie in 1964. The Bureau of Mineral Resources station at Melbourne was transferred to Toolangi in 1962 and a telemetered instrument came into operation at Melbourne in 1965. With these instruments, 175 shocks were located in Victoria in the seven years 1959 to 1966. These are listed in Table 2.

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Table 1

VICTORIAN FELT EARTHQUAKES

Year	Date Month	Day	Time GMT	Place, Intensity and Comments		Reference
1841	4			Unknown, presume Melbourne		4
1847	4	28		Melbourne. "Panic very considerable"		4
1848	10	12		Earthquake at Melbourne		3
1855	9	16	17 12	Melbourne, very extensive coastal area, estimated 140° - 143°E, 37° - 38°30' S, i.e. Western Vic. Double Shock? at Melbourne VI		4
1868	8	30	10 35	Felt Bairnsdale, Deptford, Orbost		1
1868	8	29	19 10	Felt Bairnsdale, Deptford, Orbost, Beechworth. Bright Buckland and Albury		1
1883	12	13		Tasmanian Swarm "noteworthy shock in this series" ... Biggs		17
1884	2	14	00 17	Gabo Is.	II	6
1884	2	17	6 10	Gabo Is.	III	8
1884	3	5	10 30	Gabo Is.	II	6
1884	3	18	12 20	Gabo Is.	II	6
1884	3	26	13 56	Green Cape (N. S. W.) Severe		6
1884	3	27	11 20	Gabo Is.	I - II	6
1884	6	9	10 20	Gabo Is.	II - III	6
1884	6	17	10 36	Green Cape (N. S. W.) Sharp		6
1884	7	13	4 40	Gabo Is. Pt. Albert "Noteworthy shock in the Tasmanian series" ... Biggs	III II	17
1884	8	3	2 40	Gabo Is.		6, 18
1884	8	7	12 20	Gabo Is.		6, 18
1884	8	14	9 15	Gabo Is.	II	6
1884	9	16	11 50	Gabo Is.	II - III	6
1884	9	19	10 50	Gabo Is Omeo Cape Schanck Lakes Entrance Wilsons Prom. Pt. Albert "noteworthy shock in the Tasmanian series" ... Biggs	IV Slight II - III II III - IV II	6, 4, 18, 17
1885	1	9	17 35	Mornington Cape Schanck Berwick Prahran	III II - III IV - V I - II	4, 6, 18
1885	1	30	15 05	Gabo Is.	IV - V	6, 18
1885	2	8	15 15	Gabo Is.		18
1885	2	21	10 00	Gabo Is.	II	6
1885	2	21	18 15	Gabo Is.	II	6
1885	2	27	12 00	Gabo Is. Bendoc	III II	6, 18
1885	3	9	13 20	Melbourne		18
1885	3	15	19 50	Gabo Is.	II	6, 18
1885	3	15	23 00	Gabo Is. (Time may be incorrect)	II	6, 18
1885	3	16	9 45	Gabo Is. (Time may be incorrect)		18
1885	3	20	23 25	Gabo Is. Wilsons Prom.	III - IV II - III	6, 18
1885	3	22	08 05	Gabo Is.	II	6, 18
1885	3	22	18 30	Gabo Is.	III	6, 18
1885	3	26	08 50	Gabo Is.	II	6, 18
1885	3	30	11 25	Gabo Is.	III	6, 18
1885	5	4	11 00	Gabo Is.	III	6, 18
1885	5	4	12 50	Gabo Is.	III	6
1885	5	11	13 20	Gabo Is.		18
1885	5	12	23 55	Gabo Is. V Wilsons Prom. V Bairnsdale III - IV, Bruthen III, Sale - IV Warragul III - IV Melbourne - IV Foster III - IV Omeo III - IV and at Lakes Entrance, Clydebank, Shelford, Beechworth, also at Launceston VI "climax of the series" ... Biggs		2, 4, 6, 7, 18 17
1885	5	27	07 20	Gabo Is.	II	6, 18
1885	5	31	07 56	Gabo Is. double shock	III	6, 18
1885	5	31	12 45	Gabo Is.	III - IV	6, 18
1885	7	2	16 10	Flinders IV Cowes III - IV Cape Otway II Ballarat II Melbourne and Suburbs II - III Cape Schanck V, Tyabb, Hastings IV also Sunbury, Kilmore, Wilsons Prom., Lakes Entrance, Gabo Is. At Launceston II		6, 7, 18
1885	7	3	14 57	Melbourne		18
1885	7	16	22 15	Gabo Is.	II	6
1885	8	1	05 00	Gabo Is.	II	6, 18
1885	8	1	15 18	Gabo Is.	III	6, 18

Table I (Contd)

Year	Date Month	Day	Time GMT	Place, Intensity and Comments	Reference
1885	8	19	18 32	Gabo Is. III	6, 18
1885	9	11	09 25	Gabo Is. III - IV, Omeo II, Wilsons Prom. II, Flinders II. Also Launceston, II	4, 6, 18
1885	9	12	16 45	Gabo Is. II	6, 18
1885	10	7	23 56	Bright IV, Beechworth III, Tallangatta II, Omeo III	4, 6, 18
1885	11	1	04 52	Gabo Is. III	6, 18
1886	1	3	12 56	Gabo Is. III	6, 18
1886	3	8	04 15	Gabo Is. III	6, 18
1886	7	14	16 37	Bright IV	6, 18
1886	8	2	11 15	Gabo Is. III also Eden (N. S. W.) II	4, 6, 18
1886	11	29	17 05	Severe shock in N. S. W. Beechworth III	6, 18
1886	12	2	08 43	Cape Otway III	6, 18
1887	3	8	13 27	Gabo Is. II	6, 18
1887	8	1	20 19	Cape Otway III Apollo Bay III	6, 18
1887	11	9	16 33	Gabo Is. II Also Hobart and Eastern Tasmania	6, 18
1889	1	10	06 47	Undecipherable place name IV	6
1889	7	29	08 40	Gabo Is. III	6, 18
1889	10	27	10 16	Omeo	18
1890	10	17	21 20	Ardmore	18
1891	6	7	04 24	Rosebud V, Sorrento IV Melbourne and Southern Suburbs II - IV also felt at Queenscliff, Myrnion near Ballarat and Frankston	4, 6, 18
1891	6	8	04 08	Melbourne	18
1891	7	5	10 20	Koriot III (thunderstorm ?)	6, 18
1891	7	9	05 50	Walhalla III felt from Toongabbie to Woods Point	6, 18
1891	7	9	09 40	aftershock of preceding Walhalla	6, 18
1891	7	30	17 40	North Melbourne II	6
1891	10	20	06 20	Grantville III ?	6, 18
1892	2	26	16 50	Severe shock felt throughout Tasmania. In Victoria : Gabo I IV - V, Wilsons Prom. IV, Foster III - IV, Omeo II, and at Welshpool, Cape Everard, Grant and Little Yarra. Also felt at Genoa (NSW) Location by Hogben about 41.4°S 153.8°E	4, 6, 16
1892	1	26	16 55	Aftershock of preceding	4, 6
1893	5	20	16 37	Cliffy Is. III	6
1893	7	21	18 15	Omeo	6
1893	7	22	15 35	Carisbrooke III? Castlemaine	6
1893	7	22	15 55	Aftershock of preceding	6
1893	7	22	16 20	Second aftershock of preceding	6
1893	10	9	12 43	Seymour II	6
1893	12	23	14 36	Flinders IV - V, Cape Schanck II - III also at Mornington and Mount Martha Multiple shock?	6 (reference 4 implies 1892)
1894	7	11	22 40	Grant III	6
1894	11	22	(03 15)	Gabo I II, Cape Everard III	6
1894	12	10	08 20	Omeo II	6
1895	5	8	10 50	Cape Otway II - III	6
1896	2	1	16 30	Cranbourne III - IV	6
1896	3	28	07 30	Gembrook II	6
1896	5	9	10 34	Warragul II ? Drouin III - IV also felt at Longwary, Bunyip, and Neerim South	6
1896	5	30	?	Yinnar II ?	6
1896	8	13	11 30	Omeo II also at Harrietville, St. Bernard's and Alexandra	6
1897	3	29	11 55	Kerang, Western Victoria V also at Wandella Lakes	6
1897	5	10	05 30	The Kingston S. E. earthquake. Recorded Melb. at 3. 35 at Kingston; VIII - IX	4, 6
1897	6	4		Harrow (Western Vic)	19
1897	9	26	19 00	Omeo	6, 19
1898	1	29	11 20	Yea II - III	6
1898	2	5	01 40	Warburton IV	6
1898	9	6	04 15	Alexandra V, Yea IV, Healesville II also felt at Tallarook	6
1898	11	22	01 40	Mansfield IV	6
1898	12	20	(05 35)	Goornong V	6
1899	1	31		Canterbury . II recorded by the Melbourne Observatory	6

Table I (Contd)

Year	Date Month	Day	Time GMT	Place, Intensity and Comments	Reference
1899	2	5	03 10	East Malvern (doubtfully)and Cape Schanck III	6
1899	4	12	00 25	Stawell Wartook (Western Victoria)	6
1899	5	2	03 00	aftershock of Kingson SE earthquake of 10/5/1897	6
1899	5	21	evening	Pakenham III	6
1899	6	7	21 30	Gordon (near Ballarat) IV	6
1899	6	8	05 35	Aftershock of preceding	6
1899	6	21	18 53	Alexandra Yea III - IV	6
1899	11	23	07 15	Pakenham, Narre Warren Time reported from National Bank, Melbourne. Felt Melbourne and suburbs III - IV Geelong IV Cape Schanck IV Portarlington IV also Cape Otway, Lorne	4, 16
1899	12	1	12 55	Swan Hill (Northern Victoria) II also throughout western Riverina of N. S. W.	6
1900	2	24	14 45	Armidale Toorak	4, 20
1900	3	11	17 30	Warrnambool (Western Vic.) II	4, 6
1900	5	26	0 or 12	Mansfield	4, 20
1900	5	27	02 25	Outtrim V Foster IV Melbourne and Suburbs III and all of East Gippsland	4, 6, 7, 20
1900	6	5	10 00	Meredith Steiglitz Anakie (Central Victoria)	6, 4, 20
1900	9	4	09 10	Jamieson IV	4, 6
1900	9	16	15 00	Warrnambool (Western Vic)	4, 6, 20
1900	10	8	04 48	Myrtleford II Cheshunt Princeton	4, 6
1901	6	15	22 05	Princetown (Western Vic) Rivernook	20
1901	11	18	16 00	Walhalla	4
1901	11	19	15 40	Walhalla VII Moondarra	4, 6, 20
1902	3	8	10 30	Maldon II Mt. Alexandra (IV) also felt at Harcourt, Castlemaine	6, 21
1902	5	8	03 00	Camberwell, "suspected earthquake"	21
1902	5	16	10 00	St. Kilda "suspected earthquake"	21
1902	5	27	07 00	Kilmore (doubtful)	6
1902	5	27	a. m.(local)	Portarlington	6
1902	7	11	?	Walhalla	6
1902	7	20	19 50	Cape Everard	6, 21
1902	7	21	20 51	Yea IV? Strath Creek	6, 21
1902	8	2	09 05	Mt Buckrabanyule Marmal 36° 08'S, 143° 32' E possibly volcanic or subsidence	10, 21
1902	8	14	?	Granite Flat, near Donald (Western Vic.)	6, 21
1902	8	16	01 00	Mt Buckrabanyule	21
1902	8	29	21 30	Wangaratta district IV	6
1902	9	19	10 31	Goroke Natimuk, Western Victoria Nhill (etc.) mesoseismal area in South Australia	6, 21
1902	10	21	20 30	Walhalla Glen Allan	6, 21
1902	10	22	21 00	Moondarra Walhalla	21
1902	10	27	21 30	Hurdle Creek 36°34' 146°36'	21
1902	12	17	10 00	Cape Schanck	21
1902	12	22	12 45	Sunbury IV Flinders IV Queenscliff II also felt at Cape Schanck, Hawthorn, Mornington and Ballarat	6, 7
1903	3	27	12 12	Melbourne IV South East suburbs and West Gippsland	6
1903	3	28	17 24	Similar to preceding	13
1903	4	6	23 52	Great Warrnambool Earthquake	7
1903	4	8	09 30	Aftershock at Warrnambool	7, 21
1903	5	26	00 25	Walhalla II	6, 21
1903	6	5	19 30	Portland (double shock?)	21
1903	7	10	03 56	Maldon, Bendigo and Castlemaine (Central Vic.) IV and throughout western Victoria	21
1903	7	14	10 28	Warrnambool VII Mortlake VI felt at Geelong and Ballarat At mouth of Hopkins River, sand and mud ejected in earthquake fountains. Reported to be more severe than the earthquake in April	6, 10, 21
1903	7	20	13 45	Maldon III	6, 21
1903	7	22	19 30	Moe IV	6, 21

Table 1 (Contd)

Year	Date Month	Day	Time GMT	Place, Intensity and Comments	Reference
1903	8	4	09 32	Foster II - III Leongatha II	6, 21
1903	8	14	10 30	Port Fairy, Hamilton (Western Vic.)	6
1903	8	(18)	12 55	Hamilton (Western Vic.) III date is in doubt, may be 17th or 19th	6, 21
1903	9	4	10 45	Dunolly (Western Vic.) IV - V	6, 21
1903	9	4	15 10	Yea IV	6
1903	9	23	11 20	Mansfield II	6, 21
1904	4	9	22 05	Bright V Myrtleford IV Harrietville III - IV Albury District III - IV Dargo III - IV Ensay III - IV	6
1904	4	17	16 00	Leongatha II	6
1904	5	27	13 25	Leongatha IV - V Outtrim IV Meenlyan	6
1904	7	9	09 26	Melbourne and Southern Suburbs, and Dandenong Ranges III - V Recorded on Melbourne Observatory Seismograph	6
1904	7	13	19 00	Aftershock of previous? Southern Melbourne Suburbs III - IV	6
1904	9	22	11 45	Korumburra V	6
1904	11	6	Morning	Buln Buln	6
1905	1	27	16 00	Traralgon IV Walhalla III Moe II	6
1905	5	22	21 30	Hamilton (Western Vic.) II	6
1905	6	10	14 15	Portland and Cape Nelson (Western Vic.) II	6
1905	6	27	10 30	Ensay IV - V Swifts Creek Omeo Aftershocks	6
1905	7	1	Evening	Yea	6
1905	7	12	14 20	Portland	6
1905	7	17		Aftershock in Omeo district	6
1905	7	27		Aftershock in Omeo district	6
1905	8	20	16 00	Aftershock at Ensay	6
1905	8	20	17 45	Aftershock at Ensay	6
1905	8	21	16 00	Western Victoria or South Australia Intensity appears to be distributed irregularly Hamilton VI Natimuk and Echuca V - VII Ballarat VI - VII Rapunyip, Servicetown .. "Severe"	6, 7
1905	9	18	18 05	Grantville V San Remo	6
1905	9	29	21 30	Ringwood III - IV	6
1905	11	15	00 30	Foster, Fish Creek III	6
1905	11	22	23 30	Mount St. Bernard III - IV	6
1906	2	17	10 05	Lilydale, Olinda VI	6
1906	2	28	Morning	Berwick IV - V	6
1906	6	3		Felt in Melbourne Recorded at Sydney	6
1906	6	17	15 30	Daylesford district IV	6
1906	8	10	02 40	Mirboo North IV	6
1906	8	4	09 10	Goose Island light, Bass Strait	6
1906	9	6	14 00	Dargo	6
1906	9	14	16 30	South Yarra Recorded on the seismograph at Melbourne	6
1906	9	11	20 15	Outtrim	6
1907	1	31	07 50	Gabo I-II Cape Everard IV also Launceston, Tasmania IV - V	5, 6
1907	1	31	17 15	Berwick	6
1907	2	24	19 00	Walhalla district	6
1907	3	31	14 29	Beenak IV Southern suburbs of Melbourne IV also at Cape Schanck Recorded on Melbourne seismograph	5, 6
1907	3	31	15 20	Cowes IV Pakenham but not felt in Melbourne. Recorded on the Melbourne seismograph with larger amplitude than preceding	5, 6
1907	4	4	22 25	Stawell (Western Vic.) III - IV	6
1907	5	4	Morning	Wartook (Western Vic.) III - IV	6
1907	5	16	10 00	North Geelong IV	6
1907	5	18	07 00	Tolmie, Mansfield Atmospheric phenomena noticed	6
1907	5	5	02 45	Ararat (Western Vic.)	6
1907	5	27	15 47	Maldon IV Bendigo Castlemaine Harcourt	6
1907	5	29	23 50	South Australia Felt at Casterton IV Apsley and Edenhope Recorded at Melbourne	6

Table 1 (Contd)

Year	Date Month	Day	Time GMT	Place, Intensity and Comments	Reference
1907	6	8	16 05	Cape Otway	6
1907	6	25	18 04	Anglesea	5, 10
1907	8	6	00 54	Warragul IV Yarragon IV – V Drouin, Bairnsdale Possibly several aftershocks	5, 6
1907	10	4	09 30	Yea IV Seymour IV – V also at Broadford, Nagambie and Windsor	5, 6
1907	12	11	08 05	Ensay	6
1908	3	22	01 00	Bealiba, Dunolly (Western Vic.)	6
1908	4	13	02 00	Hamilton	6
1908	5	6	16 00	Jamieson	6
1908	6	9	19 30	Berwick Pakenham Lilydale Korrumburra .. distinct	6
1908	6	15	14 00	Pakenham Tooradin III – IV	6
1908	7	15	19 00	Foster II	8
1908	7	23	04 00	Pakenham IV Berwick Fern Tree Gully	6
1908	10	19	11 00	Lilydale .. distinct	6
1908	10	23	17 50	Wedderburn IV – V "... very severe"	6
1908	10	23	18 50	Wedderburn "... medium" Aftershock	6
1908	10	23	21 15	Wedderburn "... light". aftershock	6
1908	10	27	08 30	Drouin, Langwarry	6
1908	11	20	04 50	Gabo Is. IV	6
1908	12	19	14 24	Castlemaine	6
1909	3	5	02 10	Alfredton	12
1909	3	28	17 57	Flinders	12
1909	5	31	16 00	Casterton IV – V	5, 12
1909	8	4	11 05	Pakenham	6
1909	11	15	03 55	Bairnsdale IV Buchan II Bruthen	6
1910	3	18	21 15	Bunyip IV Moe, Warragul, Drouin, Yarragon	5, 6
1910	10	24	08 30	Drouin IV Lang Lang	5, 6
1910	10	24	17 00	Bunyip	5, 6
1910	12	27	11 15	Korongvale Inglewood III +	6
1911	1	5	17 55	Felt South Yarra IV – V, St. Kilda and at Dandenong, but not recorded by the Milne at Melbourne Observatory	6
1911	3	7	16 10	Berwick	5, 6
1911	3	14	23 10	Kstamatite	6
1911	6	11	14 35	Portarlington IV – V	6
1911	8	26	09 15	Balmorsl	6
1911	10	27	02 50	Bealiba (Western Vic.) IV	6
1912	5	5	09 00	Maryborough IV	6
1912	8	11	07 15	Bealiba IV + Goldsborough, Eddington, St. Aunard, Dunolly, Tarnagulla	6
1913	3	2	17 45	Beechworth IV – V Benalla IV Shepparton IV Numurkah IV Wangaratta III – IV and Dookie, Tungawah	6
1913	11	26	09 50	Lilydalo III – IV and Warburton, Gembrook, Beaconsfield Upper	6
1913	11	27	04 00	Cheltenham, Port Melbourne, Mentone, Black Rock	6
1914	8	17	23 35	Bunyip IV Drouin IV Warragul IV Mirboo North IV Toolangi III and Gembrook, Korumburra, Pakenham	6
1914	9	5	11 00	Fish Creek	6
1915	2	27	12 15	Rosedale IV	6
1915	5	24	08 00	Rosedale ... Severe	6
1922	2	28	15 00	Severe at King Is., felt Melbourne, Lorne and Warragul Located by Melbourne staff from Melbourne seismogram, Toolangi magnetogram, and felt reports, at about 39°S 145°E	8
1922	4	10	10 45	Local 40°S 147.5°E by Burke Gaffney Located 39°20'S 144°20'E by Melbourne Observatory ataff in the same was as preceding King Is. VI Bellarine Peninsula and Point Nepean V – VI	7, 8
1922	11	20	10 30	Tallangatta	8
1922	12	9	05 20	Warrnambool	8
1929	12	28	01 22	Located at 40°S 147.5°E by Burke Gaffney	7
1931	3	13	21 11	Felt Melbourne suburbs, Geelong and also on N.W. coast of Tasmania Melbourne: e 21:11:04	15

Table 1 (Contd.)

Year	Date Month	Day	Time GMT	Place, Intensity and Comments	Reference
1932	2	14	15 27	Felt Flinders Island and at Fingal (Taa) Melbourne: i 15:27:38	15
1932	9	2	18 22	Mornington earthquake located by Holmes 38°15'S 145°E. The month given in Burke-Gaffney appears to be in error	7, 8, 9
1932	9	2	20 35	Aftershock of preceding Melbourne Milne Shaw: i 20:35:28	11
1932	9	2	20 41	Aftershock of preceding Melbourne Milne Shaw: i 20:41:07	11
1932	9	21	05 00	Benalla. Earthquake swarm with intensity up to VI at Benalla, but not felt even so close as Winton (6 miles) Glenrowan (14 milea) or Violet Town (16 miles). Activity continued for some months.	8
1932	10	9	16 30	Boort (Western Victoria)	8, 11
1932	10	9	20 10	Boort Aftershock	8
1932	10	9	23 00	Boort Aftershock	8
1932	10	18	21 40	Boort VI	8, 11
1932	10	20	00 30		11
1932	10	26	03 08	Felt Boort, Castlemaine, Pyramid Hill, Bridgewater. Melbourne : i 03:08:04 May have been several shocks in this series	8, 11
1932	12	23	14 16	Belgrave V - VI also felt at Berwick, Tooradin, Pakenham and Nar Nar Goon Melbourns: i 14:16:44	8, 11
1935	6	18	17 47	Felt N. E. suburbs of Melbourne Melbourne: i 17:47:29	11
1937	6	17	19 54	Felt at Ferntree Gully, Berwick and eastern suburbs Melbourne: eS 19:54:57	11
1938	3	24	20 04	Reported from Bright, Yarrawonga, Beechworth, Croydon and from Southern Riverina. Melbourne: 20:04:40	11
1938	5	22	21 41	Local shock or explosion, recorded on Melbourne seismograph. No felt reports. Melbourne: i 21:41:15	11
1939	3	31	07 55	Felt in suburbs Melbourne: i 07:55:21	11
1939	4	5	12 59	Felt Geelong and Portarlington, Lorne, suburbs of Melbourne, Kilmore and Ballarat. Recorded on Melbourne seismograph, date appears in error in Burke-Gaffney Melbourne: i 12:59:52	11, 7
1939	10	29	13 24	Felt Armidale, Camberwell, and Cowes, Dalyston *Melbourne: i 13:24:22*	*11*
1939	11	29	15 03	Felt S. Eastern suburbs. Cowes and Wonthaggi Melbourne : i 15:03:07	11
1939	12	15	00 25	Felt Auburn Melbourne: i 00:25:05	11
1940	1	31	18 54	Felt S. E. suburbs Melbourne: i 18:54:08	11
1941	11	4	02 33	Melbourne: i 02:33:15	15
1942	8	1	12 39	Felt in N. E. Victoria. Melbourne: iP 12:39:11	15
1944	11	2	14 05	Cerberean Range Earthquake. Felt throughout Central Victoria. Location of mesoseismal area about 37.5°S 146°E (Gaskin) Melbourne: i 14:05:42	14, 15
1945	5	14	03 03	May be regional Melbourne: P 03:03:45	15
1946	8	15	14 37	Felt Brighton. Caulfield. Point Ormond and Glen Iris. Melbourne: i 14:37:39	15
1946	9	14	19 49	S-P=23 sec. Located 40°S 147°E by Burke-Gaffney. Melbourne: P 19:49:54	7, 15
1947	1.	5	07 00	Burwood faint tremor. No record at Melbourne at the time	15
1947	6	9	07 03	Colac. Melbourne: i 07:03:42	15
1947	11	16	09 19	Probably local shock. Melbourne: iS 09:19:49	15
1948	1	16	11 20	Probable local shock. Melbourne: i 11:20:18	15
1948	3	13	17 47	Probable local shock. Melbourne: i 17:47:48	15
1948	4	28	19 41	Probable local shock. Melbourne: i 19:41:06	15
1948	5	26	01 00	Felt Malvern and Black Rock. Melbourne: o 01:00:02	15
1949	3	19	18 39	Probable local shock. Melbourne: iP (?) 18:39:22	15
1957	2	14	02 29	Felt Clayton, Doncaster, Mentone	22
1957	4	6	08 35	Felt Quambatook, Kerang, Dumosa. Melbourne: 08:35:22. Located by Melbourne Observatory at 143°19'E, 35°55'S	22
1957	8	16	06 03	Felt 7 miles East of Nagambie	22
1957	8	16	19 16	After shock	22
1957	8	18	20 19	"	22
1957	8	21	12 10	"	22
1957	8	21	12 19	"	22
1957	8	31	14 56	Felt Doveton, Harkaway and Dandenong	22
1957	10	19	10 49	Foster. Fish Creek, Walkerville	22
1959	1	19	08 52	Felt southern and Eastern suburbs of Melbourne III - IV	22
1959	3	15	12 38	Felt Merton	22
1959	3	25	12 30	Felt Hughesdale	22
1959	6	1	23 35	Seaford	22
1959	6	1	03 00 to 03 30	Seaford snd Carrum	22

In this table, epicentres are expressed to the third decimal place, and origin times to 0·1 sec, all with standard errors (Hald 1952), when a solution has been made using a computer programme developed from Flinn (1960). The focal depth is normally the least reliably determined parameter, and depths estimates that have failed to converge are bracketed. Fortunately, the epicentral location is relatively insensitive to inaccuracies in the depth estimate.

Next most reliable are the locations made graphically on a scale of 1:1 million. These are expressed in degrees and minutes, with origin times to the nearest second. It has not been possible to determine focal depths, nor error estimates, for these locations.

In all cases, a comment is given showing the location of the nearest named feature on the Geographic Series maps. Reliability is further distinguished by the qualification 'probably' for shocks that could be located to only a few tens of kilometres, and 'possibly' where gross errors may exist: for example, if only two stations recorded recognizable signals, and a choice of intersections had to be made.

All locations were made using the same simple model of the Earth's crust and mantle, consisting of 37 km of material with P velocity 6·01 km/sec and S velocity 3·61 km/sec, over a mantle of P velocity 8·16 km/sec. Recent work, however, indicates that there are probably two main crustal layers, that the Mohorovičić discontinuity dips to the south from the Snowy Mountains, and that the mantle P velocity is below 8 km/sec (Underwood 1967, Chap. 6). Many of the tabulated locations, especially those in Bass Strait and along the south coast might therefore be biased perhaps as much as 10 km south of their true positions. Relocation, however, will have to be deferred until the velocities and structures under Victoria are better known.

'Magnitudes' have been calculated from the maximum double amplitude on the vertical short period seismograph records. A divisor expressing the ratio of the velocity magnification of each instrument in the period range ½ to 1 sec to that of a Wood-Anderson instrument in standard adjustment has been applied to reduce amplitudes to 'equivalent Wood-Anderson trace amplitudes', which have then been reduced to magnitudes using the nomogram devised by Nordquist (Gutenberg and Richter 1942). The divisors are:

Canberra	18	Buchan	5
Snowy Stations	40	Mt Tassie low gain	2
Bogong Mk I	4	Mt Tassie high gain	40
Bogong Mk II	40		

Although this method does not take account of the possibility of variation in the ratio of horizontal to vertical movement, it not only gives internally consistent results, but also produces numbers consistent with the local magnitude (M_L) scale of Richter (1935), as comparison between Wood-Anderson and Benioff short period vertical records from the same station have shown (Cleary 1963).

Where the magnitude is bracketed, some doubt as to the correct value exists. The value adopted is conservative, and no large shocks are involved.

It is interesting that some earthquakes were large enough, and therefore recorded sufficiently widely, to be located during the routine work of the United States Coast and Geodetic Survey (now known as the National Ocean Survey). Seven of these locations, all in Bass Strait where locations using local stations suffer from inaccuracy due to poor network geometry and velocity bias, have been adopted in the table. These are marked USCGS. Depths are restricted where an (R) appears after the value. The magnitudes tabulated, however, are local-scale magnitudes as described above, not the body wave magnitude (m) quoted by the USCGS, which is generally smaller in this range by more than half a unit.

These epicentres have been plotted on a map in Fig. 2. The number is the magnitude, as follows:

x	event inadequately located, or no magnitude scaled.	
1	magnitude	1·0 to 1·9 inclusive.
2	,,	2·0 to 2·9 ,,
3	,,	3·0 to 3·9 ,,
4	,,	4·0 to 4·9 ,,
5	,,	5·0 and over.

A circle indicates a swarm or aftershock sequence, the number being the magnitude of the largest shock of the series.

Several features displayed by this map are worthy of notice:

(1) All the earthquakes appear to be in the Earth's crust, none in the mantle.

(2) The concentration of shocks around Corner Inlet and the South Gippsland Hills is well known. Aftershock sequences are often observed in this area.

(3) There is a preponderance of earthquakes in the eastern half of the State rather than in the west. All the recording stations are east of Melbourne so that the identification and location of a shock is favoured in the east. But the same effect occurring in the historical data and shown in Fig. 1 indicates that this is a real difference, with tectonic significance.

Table 2

Earthquakes located in Victoria 1959-1966

Date	Time GMT	SE (sec)	Lat.	SE (km)	Long	SE (km)	Depth	SE (km)	Mag	Comments
					1959					
28 Apr	08:09:00								3.3	45 Miles South of Cape Everard
23 Jul	16:41:00		36°19'		146° 33'		0		3.0	Near Eldorado, N. E. Vic.
					1960					
28 Jan	23:36:56		36.75°		147.1		15		(4)	Bright (refer Cleary, 1963)
28 Apr	04:47:58.2	10.9	37.768	71	148.440	68	depth intermediate		3	5 km south of Orbost
3 May	02:20:04								3-3/4	South Gippsland near Corner Inlet
4 May	00:42:50								3	Wonnangatta valley
16 May	02:55:16.8	56	37.334	339	147.841	698			2-1/2	Near Mt. Ellery, E. Gippsland
25 May	09:32:28								2-3/4	Eastern Bass Strait
29 May	02:41:03.1	0.4	36.515	3.8	147.428	1.8	(-18)	3.0	2-1/2	Mitta Mitta
1 June	05:18:47.6	3.3	36.763	23.7	145.354	26.6	12.4	13.5	3-1/2	Nagambie
4 June	12:43:10								4-1/4	South of Cape Otway
21 June	07:09:28		36°		146°42'				2-1/4	Murray valley west of Albury.
20 Oct	20:22:04.6	3.2	38.563	38.6	146.449	13.3	8.4	24	4	Corner Inlet
21 Oct	14:47:57.0	35	38.895	310	146.496	76			3.9	Wilsons Promontory
4 Nov	17:55:27		37°		148°18'				2	West of Mount Bulla, E. Gippsland
5 Nov	06:31:15.7	1.0	37.121	5.5	148.302	4.8	(-14)	47	2-1/2	South of the Delegate River
6 Nov	13:29:28		37°06'		148°09'				1-3/4	N. W. of Mt. Statham, E. Gippsland
20 Nov	21:09:52.7	0.3	36.845	5.2	147.304	3.0	(-1.3)	2.6	2-1/4	N. W. of Omeo
23 Dec	09:39:52.6	3.7	37.754	21.7	148.281	15.6	22.1	9.8	3	Between Orbost and Nowa Nowa
24 Dec	16:42:08.5		39°		143°30'		77		5-1/4 - 5-1/2	Cape Otway (U. S. C. G. S.)
					1961					
22 Jan	14:43:55		39° 30'		155°30'				4	South Tasman Sea
22 Jan	18:39:45		40°		155°30'				4	" " "
3 Feb	14:37:45		40°		148°30'				4	Near Flinders Island
28 Mar	04:02:08.9	3.7	37.620	15.7	148.094	24.8	(-23)	22.3	2-1/4	South Buchan
10 Apr	14:10:32.6	4.3	37.142	18.7	144.051	4.6	(-5.6)	34.6	4	South of Maldon. Felt: Maldon
11 Apr	00:35:23.4	13.1	38.281	93	146.468	25.7	(46)	57	4	South Gippsland Hills.
15 Apr	06:40:10		36°15'		146°30'				2-1/2	Vicinity Ovens River
28 Apr	23:09:50								2-1/4	Probably S. W. of Mitchell River
1 Jun	09:53:07.7	12.7	38.567	21.5	144.531	14.1	5.3	110	4	Northern Bass Basin
1 Jun	13:19:51		38°18'		144°06'		29		4-1/4	Bass Strait (U. S. C. G. S.)
12 Au,	21:01:58		37°24'		149°06'				2	S. W. of Mt. Kaye, E. Gippsland
14 Aug	19:59:43		37°36'		148°12'				2-1/2	Near Nowa Nowa
12 Sep	07:13:09.4	4.4	40.686	29.2	156.609	183	(576)	170	4-1/4	South Tasman Sea
15 Sep	05:09:40.1	2.0	37.554	26.8	147.294	15.6	22.0	10.5	3-1/2	Near Tabberabbera
9 Oct	23:43:14.3	21.6	39.211	155.3	145.882	45.4	(49.4)	76	4	Tarwin Meadows
9 Oct	23:59:28.4								3-1/2	Aftershock
10 Oct	00:03:00.1								3-1/2	"
10 Oct	00:06:15								2-3/4	"
10 Oct	00:08:00								2-3/4	"
10 Oct	08:45:31								3-1/2	"
10 Oct	13:36:08								4	"
10 Oct	20:50:44								2-3/4	"
12 Oct	22:48:01								3	Probably Aftershock
13 Oct	06:47:09								3.4	" "
19 Oct	15:23:49									Probably near Walhalla
22 Nov	21:55:16.8	19.7	30.017	84.4	146.028	74.9	(-69)	129	3-1/2	Yarrawonga

Table 2 (Contd)

Date	Time GMT	SE (sec)	Lat.	SE (km)	Long	SE (km)	Depth	SE (km)	Mag	Comments
					1962					
10 Jan	05:40:31		$38^\circ 30'$		$146^\circ 30'$				3-3/4	Corner Inlet
10 Jan	06:12:17								3-3/4	Aftershock
10 Jan	19:21:10								1-3/4	Probably near Bonang
11 Jan	09:10:49.4	21.9	37.804	137.3	148.811	352.3	(4296)	17	2-1/2	Cape Conran
7 Mar	14:17:14									Probably double shock in the vicinity of
7 Mar	14:17:27									lake Wellington
27 Mar	17:54:22.2	0.2	37.920	2.6	146.547	1.1	5.9	0.8	3-3/4	East of Walhalla
11 Apr	18:28:58		$38^\circ 54'$		$146^\circ 20'$				3-1/2	Wilsons Promontory
27 May	11:34:28.9	17.2	38.582	22.4	146.385	61.1	(-32)	176	3-1/2	Wongip
27 May	11:49:07.8								3	Aftershock
22 June	06:12:03									Vicinity of Foster
5 Jul	13:00:02.7	0.5	37.173	2.1	148.018	5.8	(-4.5)	2.4	2-1/2	West of Mt. Stratham
30 Jul	11:43:11								1-1/2	Vicinity of Deddick River
30 Jul	11:44:54								1-3/4	" " "
30 Jul	11:47:25								1.6	" " "
30 Jul	11:50:59								1.8	" " "
8 Aug	22:46:06									Indeterminate, possibly Northern Goulburn Valley
17 Aug	03:45:12		$38^\circ 00'$		$148^\circ 12'$					Off coast south of Orbost
17 Aug	03:45:18									Probably Aftershock
20 Aug	06:07:27								3	Possibly in vicinity of Maffra
26 Sep	09:02:57.3	1.3	36.497	11.8	147.146	8.6	16.3	10.5	2-3/4	Eskdalo - Upper Gundowring
13 Oct	07:59:44								1-3/4	Probably south of Bonang
20 Nov	12:15:28								3-1/2	Near Foster
15 Dec	21:41:32								3-1/4	Corner Inlet
15 Dec	21:59:55									Aftershock
26 Dec	10:51:27.6	2.4	37.568	27.7	146.888	12.4	(-6)	12	3-1/4	Mount Wellington
31 Dec	19:10:25.6	2.6	36.304	20.6	146.405	14.0	(-23)	17	2-3/4	Wangaratta
					1963					
14 Jan	06:31:54.1	2.5	36.557	18.2	146.717	11.7	(-21)	27	3	Myrtleford
28 Jan	02:33:34.4	0.7	36.406	8.3	146.547	3.6	6.7	2.6	3.1	Everton
28 Jan	12:02:25.6	0.4	37.058	7.5	146.684	4.2	5.7	4.6	3	Mount Speculation
7 Feb	05:55:00								2-1/2	Possibly Wilsons Promontory
8 Feb	01:06:48								2.9	Probably vieinity of Upper Howqua River
15 Feb	11:50:50								2-1/4	Possibly vicinity Lakes Entrance
6 Mar	09:00:23.5	14.2	37.316	51.5	148.531	42.9	(-22)	179	3	East of Mount McDonald
9 Mar	01:00:57		$37^\circ 12'$		$147^\circ 33'$				2-1/4	Omeo-Tongio district
16 Mar	09:38:52		$38^\circ 36'$		$146^\circ 18'$				3	South Gippsland Hills
29 Mar	00:10:35.7	34.8	37.898	270	146.331	108	18.9	211	3-1/2	Walhalla - Mount Baw Baw
2 Apr	18:09:12		$37^\circ 06'$		$144^\circ 21'$				3-1/4	East of Castlemaine
14 Jun	19:23:47.8	3.7	38.657	14.9	146.425	5.7	1.6	25.7	4-3/4	Welshpool (also U. S. C. G. S.)
16 Jun	18:43:47								3-1/2	Aftershock
24 Jun	07:21:49								2.9	"
2 Aug	09:52:24								3-1/2	Probably Strathbogie Ranges cast of Euroa
29 Aug	05:10:		$36^\circ 48'$		$147^\circ 30'$				1-3/4	Near Glen Wills
11 Nov	23:49:49.5	0.8	37.888	4.8	148.090	7.2	7.9	3.8	2-1/2	Off Lakes Entrance
11 Dec	02:22:37								(2-1/2)	Possibly west of Bendigo
25 Dec	08:48:30		$37^\circ 50'$		$146^\circ 12'$				2.9	Upper reaches of the Tyers River.

Table 2 (Contd)

Date	Time GMT	SE (sec)	Lat.	SE (km)	Long	SE (km)	Depth	SE (km)	Mag	Comments
						1964				
4 Feb	19:36:12.6	0.8	36.865	19.9	146.545	8.5	36.3	13.2	2-1/2	Rose River near "Bennies"
16 Mar	06:45:24.2	0.6	36.149	3.0	147.109	3.4	10	3.4	2-1/4	Bethangra. N.S.W. near Hume Weir.
18 Mar	02:03:08								(2-1/4)	Possibly South Gippsland Hills
9 Apr	06:34:00								2-1/4	Probably near Albury
10 Apr	04:14:32								(2-1/2)	North East Highlands
28 Jun	13:38:50.2	3.7	36.413	14.1	145.244	25.4	4.8	13.7	3-1/2	Goulburn Valley near Tatura
11 Aug	07:31:04.9	10.1	39.037	65.4	146.330	24.7	depth indeterminate		3-1/4	Wilsons Promontory
26 Aug	05:49:53								(3)	Probably South Gippsland Hills
26 Aug	05:51:43								(2-1/2)	" " " "
27 Aug	01:10:47								(2)	" " " "
28 Aug	21:32:12								(2-1/2)	Probably off Lorne and Apollo Bay
9 Sep	04:24:06								(2-3/4)	Possibly off Cape Woolami
18 Sep	20:03:10								(2-1/2)	Probably Northwest Bass Basin
18 Sep	22:38:04.7	1.2	37.338	7.3	147.785	5.3	(-8)	7.5	2-1/2	Near Ensay
23 Sep	15:43:02									Possibly vicinity of Ballarat
26 Sep	10:27:05								(2-1/2)	Corner Inlet
12 Oct	22:45:25.8	10.8	38.059	120	146.276	57	36.8	57	3-1/4	Near Moondarra
15 Oct	01:39:24								(2-1/2)	South Gippsland Hills
23 Oct	00:01:(10)									Indeterminate Regional Earthquake
25 Oct	10:32:44								(3)	Bass Basin between King Is. and Wilsons Promontory
30 Oct	03:13:25								(2-3/4)	" " " "
10 Nov	21:35:10								3-1/2	West of Nagambie
14 Nov	10:53:01		40°00'		144°18'		33 (R)		4.4	Bass Strait between King Is. and N.W. Tasmania (U.S.C.G.S.) Felt.
17 Nov	21:16:18.5	1.0	38.416	8.8	146.352	5.5	16.1	18.2	4	Boolara South
18 Nov	19:29:52								1-3/4	Aftershock
18 Nov	19:30:39								1	"
16 Dec	05:32:20		36°40'		145°33'				(3)	Near Euroa
						1965				
6 Jan	19:44:27.5	1.3	38.844	8.5	145.973	4.7	9.6	4.2	3-1/2	Waratah
9 Jan	09:15:06.3	20.5	38.161	121	146.962	57.7	(-30)	141	2-3/4	Kilmarny South
13 Jan	02:13:12.0	1.1	37.296	3.9	148.072	1.9	26.5	12.7	2-1/4	Timbarra
19 Jan	05:44:08.3	7.2	36.396	51.5	146.200	24.7	(-4)	41	2.4	Near Wangaratta
19 Jan	20:46:53								3	Near Euroa
21 Jan	16:28:(40)								(2-1/2)	Possibly northern Bass Basin.
7 Mar	07:37:11								2-3/4	Big River valley. near Eildon Weir.
16 Mar	13:16:01								2-1/2	Upper Howqua valley
17 Mar	05:21:45.2	37.6	37.087	106.5	146.154	97.5	(245)	75	3.1	Merrijig
18 Mar	18:09:31.1		40°12'		149°36'		33(R)		5	Southeast of Australia (U.S.C.G.S.)
23 Mar	20:55:50								(3)	Probably Western Victoria
1 May	18:17:03.2	4.7	38.519	9.4	146.412	33.1	5.7	54.3	3-1/2	Wonyip
8 May	06:25:53.2	5.0	38.658	24.4	149.159	18.3	26.5	21.3	3-3/4	Eastern Bass Strait
10 July	02:25:47								1-3/4	South Gippsland Hills
16 Aug	17:14:17.8	0.6	37.225	1.8	146.248	1.4	14.5	22.3	2-1/4	Howqua River
3 Sep	09:12:02.8	0.7	38.711	4.0	146.467	1.5	(-16)	2.9	1.9	Port Welshpool, Corner Inlet
6 Sep	07:29:00								3.6	Probably near Castlemaine
8 Sep	06:17:23.3	0.4	38.215	3.3	146.410	1.6	16.0	2.6	2-3/4	Morwell
14 Sep	12:34:36.3		38°42'		144°12'		33(R)		5.0	Near S.E. coast of Australia (U.S.C.G.S.) Felt.
14 Sep	12:44:57								3-3/4	Aftershock
14 Sep	12:50:13								(2)	"

Table 2 (Contd)

Date	Time GMT	SE (sec)	Lat.	SE (km)	Long	SE (km)	Depth	SE (km)	Mag	Comments
							1965			
14 Sep	12:53:13		38°42'		144°18'		33(R)		5.7	Near S. E. coast of Australia (U. S. C. G. S.) Felt.
14 Sep	13:15:46								2.9	Aftershock
14 Sep	13:55:47								3.3	"
14 Sep	15:47:19								3.1	"
5 Oct	15:14:								(2)	Possibly vicinity Cape Otway
6 Oct	00:35: 04.2	2.2	36.508	11	145.070	8.8	(-3)	11	(2-1/2)	Waranga Reservoir near Rushworth
15 Oct	14:08:04								1-1/2	West of Mount Useful
24 Oct	15:48:23.8	0.7	38.193	1.9	145.708	1.3	30.6	10.7	2.1	Near Modella, N. E. of Western Point Bay
2 Nov	15:23:35								1-3/4	Few km south of Korumburra
30 Nov	18:35:20								2.4	Off Airey's Inlet
2 Dec	08:11:34								1-3/4	Probably near "The Nobbies", Phillip Island.
							1966			
16 Jan	12:37:26		39°00'		144°20'				1-1/2	Northern Bass Basin
25 Jan	21:17:43								(1.6)	Off East coast of Wilsons Promontory
10 Feb	01:46:52								(1-1/2)	Possibly Strathbogie Ranges
13 Feb	10:56:22.0	2.4	38.904	12.3	145.895	6.1	(62)	22	3.3	Cape Liptrap
23 Apr	17:26:33.3	1.4	37.080	10.0	146.275	6.0	0.9	18.6	2-1/2	Merrijig
23 Apr	17:26:56								2-1/2	Merrijig
1 May	05:09:34.5								(3)	Glen Thompson, Western District: Felt.
3 May	19:07:53.1	0.8	37.043	2.3	147.130	4.7	7.6	7.0	5-3/4	Mount Hotham
31 May	04:18:18								2-1/4	South West of Wilsons Promontory
5 July	22:28:39.4	5.3	39.647	5.6	144.964	31.9	(62)	35	4.1	South of Cape Schanck
6 Aug	15:05:23								(2)	Wallan
15 Aug	22:27:18.2	11.8	37.957	40.6	149.121	40.7	35.6	58.7	3.2	South of Cann River
30 Aug	14:27:24								(2-1/2)	Probably vicinity Bendigo
5 Sep	17:57:51.5	4.6	36.230	17.4	144.522	22.6	17.0	21.2	3.4	South West of Echuca
29 Sep	18:05:53.0	7.7	38.267	34.4	146.104	15.1	(-76)	50	3-1/4	Childers, E. Gippsland
2 Oct	05:04:54									Undetermined Victorian earthquake
8 Oct	13:21:14								(2)	Dandenong. Felt.
17 Oct	17:12:30.8	6.4	37.880	62.2	146.199	37.4	18.1	48.9	3.8	Headwaters of the Tanjil River
27 Oct	00:25:46		40°00'		154°30'		0 (R)		4-3/4	South Tasman Sea
27 Oct	01:06:22		40°00'		149°45'		0 (R)		3-1/2	East of Flinders Island
3 Nov	06:13:19								(1-1/2)	Vicinity of Cape Otway
13 Nov	20:56:15								3-1/2	Between Boort and Pyramid Hill
15 Nov	21:23:00		38°30'		144°42'				(2)	West of Cape Schanck
30 Nov	15:30:25								(2-1/2)	Possibly vicinity Pyramid Hill
15 Dec	19:08:29.1		40°24'		155°24'		33 (R)		5-1/2	South East of Australia (U. S. C. G. S.)

FIG. 2—Seismicity of Victoria 1959-1966 inclusive. The magnitude numbers are plotted at the computed epicentre. A ring indicates aftershocks; an x indicates an inaccurate location.

(4) Earthquakes located near Melbourne, and in the western part of Gippsland, are rare compared with the historical record. One difficulty in studies of small earthquakes is to distinguish these from large quarry blasts, especially round centres of population and industry, and it is possible that a few earthquakes have been wrongly rejected because they chanced to occur during working hours when blasts are likely. But there seems to have been a real diminution in seismic activity in West Gippsland.

(5) High activity occurs along the coast east of Cape Otway. The largest earthquake of the period studied, magnitude 5·7 on 14 September 1965, occurred in this area, and it was preceded by a magnitude 5·0 shock 20 minutes earlier. There were several aftershocks. The accuracy of location in this area is not good, so that the question whether the activity is associated with either or both of the faults mapped along and off this coast (Weeks and Hopkins 1967) cannot be answered by this study.

(6) An interesting feature of the seismicity is an association between earthquakes in the central Tasman Sea, near Lat. 40°S., Long. 155°E. (off the edge of Fig. 2) and others at the same latitude just east of Flinders Island. On two occasions, earthquakes of the eastern group have been followed by shocks at the western end. There have also been unassociated shocks.

	G.M.T.	Lat.	Long.		
1961 Jan. 22	14:43:55	39°30′S.	155°30′E.	M = 4	S. Tasman Sea
,, ,, 22	18:39:45	40°S.	155°30′E.	M = 4	S. Tasman Sea
,, Feb. 3	14:37:45	40°S.	148°30′E.	M = 4	E. of Flinders I.
1966 Oct. 27	00:25:46	40°S.	154°30′E.	M = 4¾	S. Tasman Sea
,, ,, 27	01:06:22	40°S.	149°45′E.	M = 3½	E. of Flinders I.

UNASSOCIATED SHOCKS

1961 Sept. 12	07:13:09	40·7°S.	156°6′E.	M = 4¼	S. Tasman Sea
1966 Mar. 18	18:09:31·1	40°12′S.	149°36′E.	M = 5	Continental slope, E. of Flinders I.
,, Dec. 15	19:08:29·1	40°24′S.	155°24′E.	M = 5½	S. Tasman Sea

A search through the results for January 1967 has not revealed any shocks near Flinders Island that could be associated with the last of these.

There does not seem to be any east-west feature in the topography of the sea floor near Lat. 40°S. that could correspond to the seismic pattern, and the central Tasman epicentres are beyond a major ridge trending NNE.-SSW. These shocks may be mislocated by a considerable distance. Soundings, and marine refraction profiles to establish mantle P velocities, preparatory to a careful re-determination of shocks in the Tasman Sea, would be worthwhile projects.

(7) Near Moondarra (Lat. 38°02′S., Long. 146°22′E.) in Gippsland, there is an active seismic area. The existence of this feature is confirmed by the number of historical reports of earthquakes felt in the area. To the writer's knowledge, its presence has not previously been noted, but as it is beside the developing industrial and population concentration of the Latrobe Valley, further study is obviously desirable.

From the present study, it appears that the epicentres are all in the hills to the north of the fault bounding the Gippsland basin, and that the active area is elongated east-west, in contrast to the generally meridional trend of the Palaeozoic in these hills. It may be significant that the bounding fault hinges in this vicinity, because the corresponding fault to the south of the Gippsland basin also hinges near an active seismic zone, in the South Gippsland Hills (Weeks and Hopkins 1967, Fig. 6).

(8) Seismicity studies based on only the larger events may be misleading. For example, the USCGS events in Table 2 would indicate hardly any seismicity on the mainland, as they are mostly in Bass Strait. But the risk of damaging shaking at a site arises largely from smaller events which may occur at short epicentral distances, and Fig. 2 shows many of these in Victoria. Table 2 is complete for all events capable of causing damage, at least for Eastern Victoria.

RECURRENCE RELATIONSHIPS

The probability distribution of earthquakes with magnitude provides a convenient summary of seismic activity. The parameters can be used for comparisons between regions, and for the calculation of extreme value statistics useful in designing engineering works.

From Table 2, the number of shocks in intervals of one half of a magnitude unit were counted, and a cumulative graph drawn (Fig. 3). The ordinate has a logarithmic scale. Fitting a formula of the type

$$\log_{10} N = A - bM$$

where N is the number of shocks of magnitude M or less, to the linear portion of the graph by eye gives

$$A = 3{\cdot}71 \quad b = 0{\cdot}6$$

Below magnitude 3½ the number of shocks recorded falls increasingly below the straight line. This is inevitable because smaller earthquakes are lost in the background of noise. For a more closely spaced network the magnitude below which earthquakes are lost is smaller. For example, the Dalton curve on the same figure is linear down to about 2½ and the Snowy curve probably down to about 2. For high magnitudes, the smallness of the sample causes some instability.

It is unusual for the b value to be so low; typical values cluster round 0·8 to 1·0 (Isacks and Oliver 1964; Ryall, Slemmons and Gedney 1966), while experiments on the fracture of heterogeneous materials give b values in the range 0·5 to 1·5 (Mogi 1962). The low Victorian value implies that there are more earthquakes of larger magnitude than might be expected from a worldwide coverage. This contrasts with the Dalton-Gunning region in New South Wales, where an analysis of the data by Cleary (1967) gives

$$\log_{10} N = 5{\cdot}1 - 1{\cdot}45\, M$$

That is to say, there are many small shocks and few large ones in the Dalton-Gunning region. The

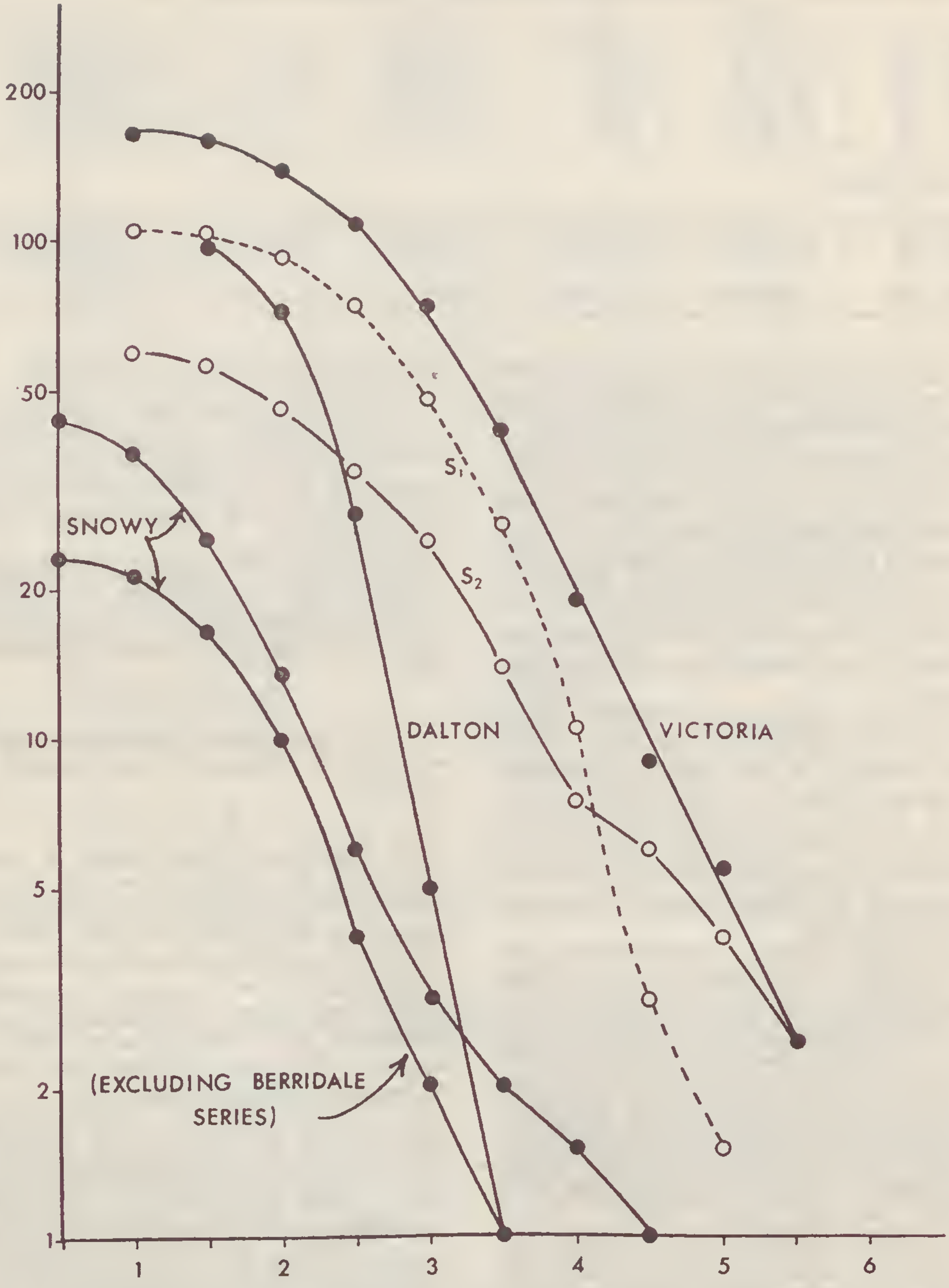

FIG. 3—Earthquake recurrence diagrams for south-eastern Australian seismic areas (see text).

data from the Snowy Mountains region extracted from Cleary, Doyle and Moye (1964) are also plotted in Fig. 3, both with and without the Berridale sequence. It shows a complicated behaviour, somewhat perturbed by the smallness of the sample, with the value of b about 0·6.

As discussed below, the Victorian data may be divided into periods before and after 1 November

1964. These are the S_1 and S_2 lines in Fig. 3. The straight line segments are

For S_1:

$\log_{10}N = 4{\cdot}14 - 0{\cdot}790\,M;\ \Delta M = 0{\cdot}5,\ N = 104$

For S_2:

$\log_{10}N = 10{\cdot}31 - 0{\cdot}397\,M;\ \Delta M = 0{\cdot}5,\ N = 60$

but the samples are rather small. The S_1 period has a normal 'b' value. The very low 'b' for the S_2 period is because there are many earthquakes of magnitude 4 and above.

TIME SEQUENCE ANALYSIS

If the earthquakes are perfectly independent, rare (that is, isolated), random events, all of which are equally probable, then the number of events per unit time interval should be distributed with a Poisson law (Lomnitz 1966). The earthquakes in Table 2 were counted in one-month intervals (Fig. 4, third histogram) and the historical data in Table 1 were counted in one-year intervals (Fig. 4, first histogram). Chi-square tests on the index of dispersion (the ratio of variance to mean) showed that there was negligible probability of either histogram being from a Poisson distribution, the major contribution to the statistic coming from the great number of zero-event intervals. Deviations from the Poisson law can be due to:

(1) Failure to detect all of the small magnitude events. That this is important can be demonstrated by removing all of the shocks $M < 3\frac{1}{4}$ (Fig. 4, second histogram), which indeed increases the number of empty intervals. However, it does not seem possible to reconstruct the distribution of all shocks, including unobserved small ones, without making some further assumptions.

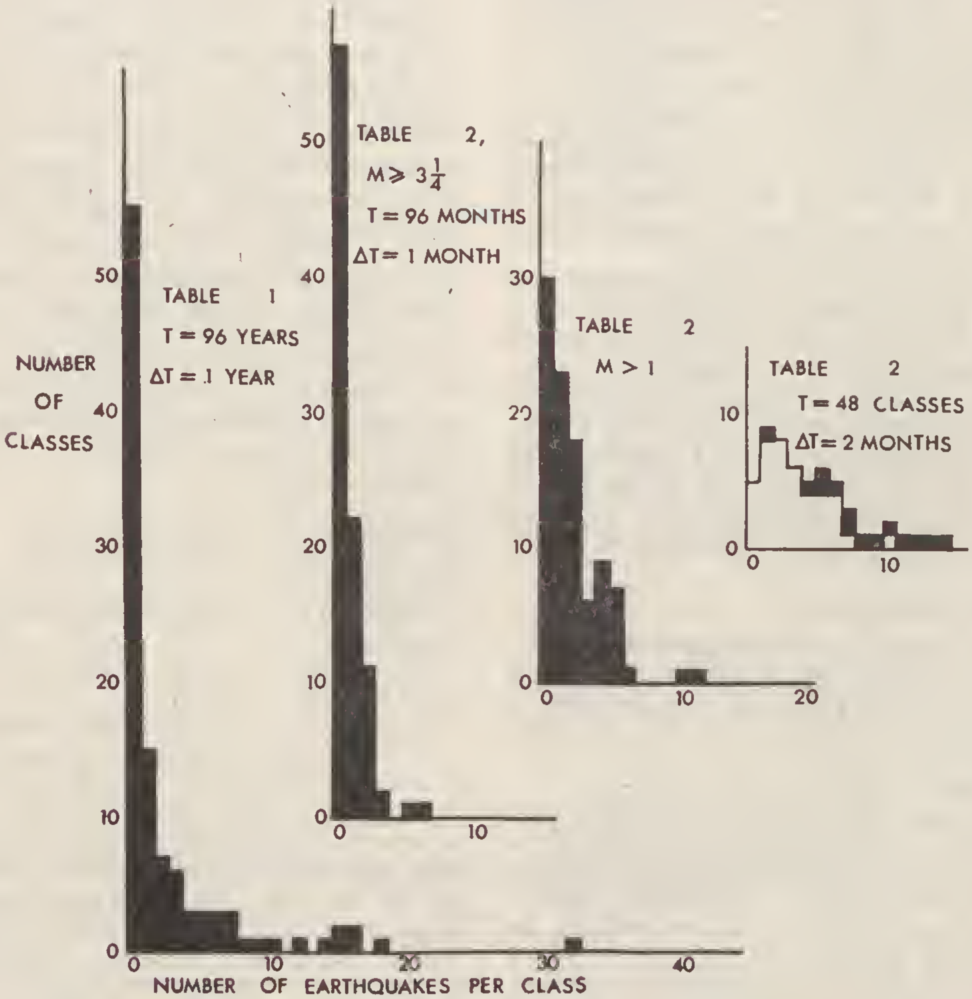

FIG. 4—Histograms of the frequency with which the time interval ΔT had the stated number of earthquakes, in Victoria.

(2) Space inhomogeneity, as demonstrated by Fig. 1 and 2.

(3) Non-stationarity of the time sequence, which can be shown to be present at the 5 per cent significance level by a Kolmogorov-Smirnov test on the cumulative count of all earthquakes as a function of time. There was a sudden significant change in trend in August 1964, with shocks in the South Gippsland Hills and Bass Strait, and about three months before the change in strain release discussed in the next section. Neither portion of the data has a Poisson distribution.

(4) Clustering of events is certainly a major reason for deviation from the Poisson distribution. An inspection of Table 2 shows several aftershock sequences, and these events are by definition not independent. But a reasonable assumption is that the influence of one shock on the probability of occurrence of a succeeding one is a decreasing function of time, so that taking counts over successively longer intervals of time should lead to closer approximations to the Poisson model. The fourth histogram of Fig. 4 illustrates this for two-month intervals. (With a small quantity of data, the arbitrary choice of starting time introduces fluctuations. Both odd and even starting months are shown, to illustrate this.) Further analysis shows that significant correlation between events persist to about two months at least.

There are not, however, any significant periodic effects in the data. This can be shown by spectral methods, but it is perhaps sufficient to remark that the index of dispersion is significantly greater than one, indicating clustering, whereas periodic data would be underdispersed. Moreover, any recurring effect would necessitate a period exceeding four months (because this is the longest interval observed between events), but correlation between numbers of events in intervals as long as this is insignificant.

STRAIN RELEASE

To gain a deeper understanding of the tectonic process it is necessary to combine the magnitude and number analyses, and this can be done by accumulating a quantity called 'strain' as a function of time:

$$\text{strain} = J^{\frac{1}{2}} = \text{antilog}\,(4{\cdot}5 + 0{\cdot}9\,M)$$

This formula is based on the energetics of a simple earthquake model, where the rocks in the vicinity of a fault accumulate elastic strain energy, proportional to the square of the strain, until it is released when the fault slips to produce an earthquake. A proportion of the energy released goes into vibrations which are recorded, and scaled in the logarithmic form as magnitude. The constants are chosen to allow direct comparison with other work. Although the model is simple linear, and elastic, we are interested mainly in changes in the time trend of strain, and need make no such assumptions about the underlying tectonic processes. The strain release computed for all the earthquakes of Table 2 is plotted in Fig. 5.

Clearly, two quite different types of tectonic regime have been acting. The first appears to have commenced about 1959 although detailed results did not begin to accumulate until this time, when new stations began to operate. Strain release is proportional to the logarithm of time:

$$S_1 = (0{\cdot}878 \log T - 2{\cdot}15)\,10^{10}$$

where S is the strain release in $(\text{erg})^{\frac{1}{2}}$ and T is the time in days from 1 January 1959. Commencing in October or November 1964, strain release has been linear with time

$$S_2 = (0{\cdot}002135\,T - 3{\cdot}86)\,10^{10}$$

and this new regime continues to the end of 1966.

This may be interpreted as a 'locking' sequence (Benioff 1955). During the S_1 regime, the parts of the area were locked tightly together so as to act as a single unit to external strain. The earthquakes within the area were in the nature of readjustments of strain accumulated from prior to locking, and the rate of strain release at any one time was proportional to the strain remaining at that time. In the second half of 1964, the locking began to weaken, and it is tempting to identify the magnitude 4·4 earthquake in a somewhat unusual position between King Island and north-west Tasmania on the 14 November 1964 as the final 'breaking' of the lock. Since then, strain has been released at a rate governed by the rate of accumulation, which is linear with time. This rate is only one to ten per cent of the rate in active regions, however:

Victoria	$B = 0{\cdot}2 \times 10^8$
Deep Kermadec	$B = 161{\cdot}0 \times 10^8$
Deep South American	$B = 73{\cdot}0 \times 10^8$ after 1932
Deep South American	$B = 15{\cdot}9 \times 10^8$ before 1922
Shallow South American	$B = 153{\cdot}0 \times 10^8$ after 1922

(*data from Benioff* (1949, 1955))

The form of the S_1 curve is also often observed in aftershock sequences; extrapolating to earlier time indicates an initiation time no earlier than the end of 1958. There seems to have been no large enough shock in Victoria during this time, but the magnitude 5 earthquake of 18 May 1959, near Berridale in the Snowy Mountains (Cleary, Doyle and Moye 1964), may have locked the Victorian region, and initiated the S_1 regime. One

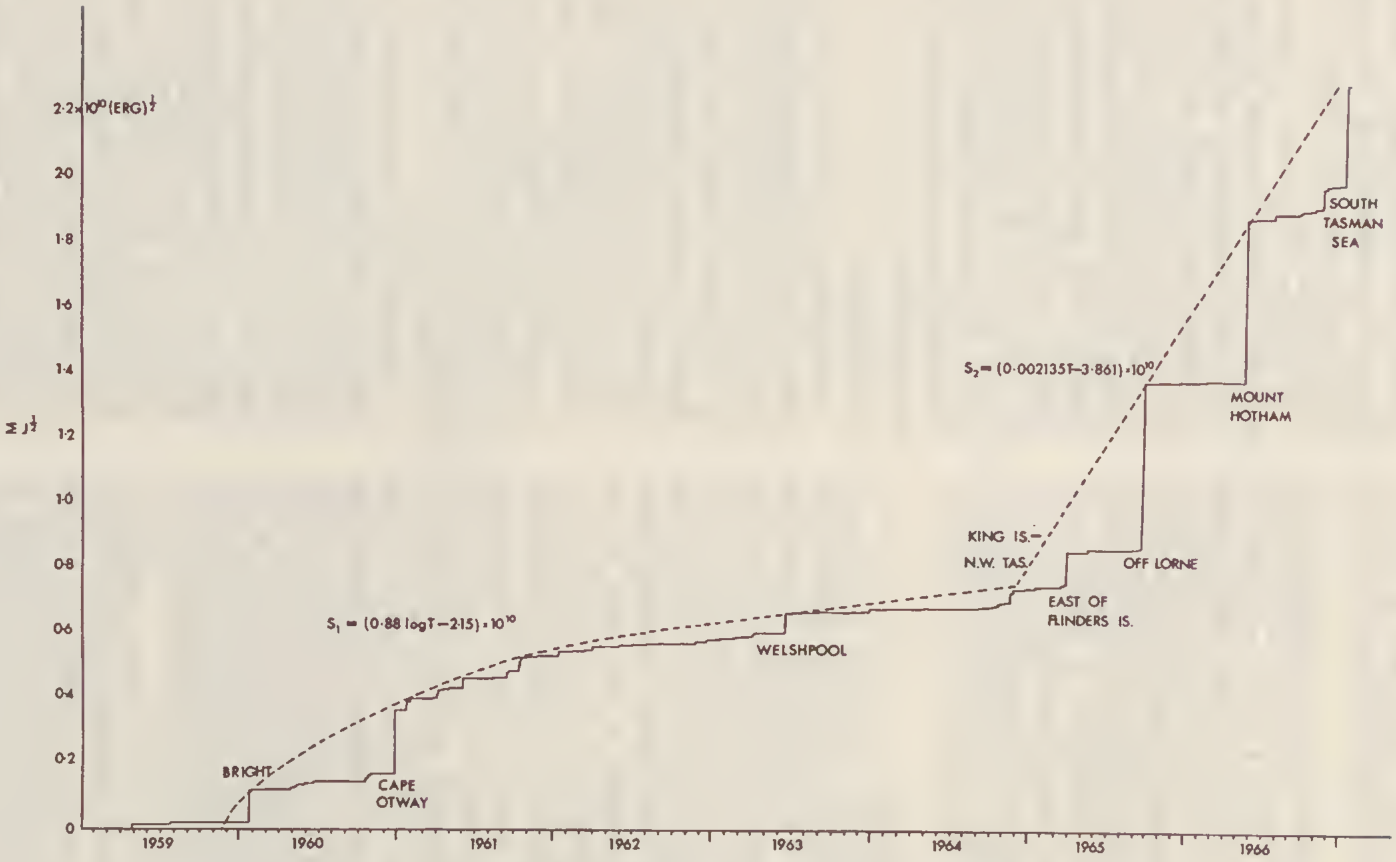

FIG. 5—Strain release diagram for Victorian earthquakes.

might speculate that while the Victorian area was not releasing externally accumulating strain, but responding as a unit, the strain built up in adjacent regions until a different locality failed, and this was the Robertson area south of Sydney, where a magnitude 5½ shock occurred on 21 May 1961.

To bring the analysis as far as possible up to date, the events from the end of 1966 to mid-1970 have been examined in the same fashion. Both numbers of events and their strain release decreased from 1967 to mid-1969. On 20 June of that year, a magnitude 6·0 earthquake occurred at Boolarra in South Gippsland, followed by many aftershocks. The strain release for this new data is definitely less than during the S_2 regime, and it does not seem to form a continuation of earlier activity according to any recognizable creep law. It seems clear that a new locking sequence is beginning in Victoria but a detailed analysis is not yet possible.

NODAL ANALYSIS

When an earthquake is recorded at a number of stations, the direction of ground motion of the initial P impulse is found to be 'up' at some, and 'down' at other sites. This distribution is a mappable quantity, and if the seismic rays are traced back to correct for the known structure of the earth, the corrected pattern is very simple. The lines dividing 'up' from 'down' are usually found to be readily interpreted as the traces of two 'nodal' planes orthogonal at the earthquake focus. By hypothesis, one plane is identified as the 'fault' plane in which motion has occurred, and the other as the 'auxiliary' plane, but from P observations alone it is not possible to decide which is which. For details of the theory and method see Cleary, Doyle and Moye (1964), Cleary (1963) and Underwood (1967). By further hypothesis, principal stress axes may be deduced from either plane if an angle of slip is assumed. Usually the angle of slip is assumed to be 45°; i.e., it is assumed that the faulting occurred on the plane of maximum shear stress, because the two sets of principal stress axes coincide in this case. Alternatively, some assumption is made about the stress, so that the slip angle can be calculated.

Only a few of the largest Victorian earthquakes have been sufficiently well recorded to enable this method to be employed. These are the Bright (1960), Cape Otway (1960), and the shock off Lorne (1965). Summarizing these, along with all the other earthquakes in south-east Australia for which solutions have been obtained (Cleary 1963, Underwood 1967) by plotting poles and axes on a lower hemisphere Wulff stereogram, and assuming 45° angle of slip results in the consistent pattern shown in Fig. 6. Open symbols represent reverse fault movements, the squares being the poles of the preferred fault planes, and the circles poles of the auxiliary planes. The principal stress axes are represented by P for compression and T for tension axes, with a plus sign for the intermediate stress axis.

It is apparent that there is a tendency for tension axes to be near vertical, and the compressive axes cluster between west and northwest, but with moderate plunges. Equilibrium of the whole area demands that the average compressive stress be horizontal. Assuming this to be the case, the angles of slip come out to be rather uniformly distributed from 0 to 90°, and a chi-squared test shows that there is no preferred average angle of slip. The average azimuth of the P axes rotated to the horizontal is 298°. If the pattern indicates the response of south-east Australia to tectonic forces, then these forces are compressions from southeast and northwest.

DISCUSSION

Earthquakes in Victoria occur mainly in the eastern half of the State, and there are three active areas: in the South Gippsland Hills, near Moondarra, and off the Otway coast. The shocks are not independent events, and appear to be in response to horizontal compression on a southeast-northwest line. In the period studied instrumentally, two types of behaviour occurred. The first commenced about the end of 1958, the strain release being logarithmic with time, and the recurrence ratio b being close to a normal value of 0·8. Then from mid-November 1964, strain release became linear with time, and there was an anomalously large number of earthquakes of magnitude 4 or greater.

The picture which has emerged from the seismic studies foreshadowed by Jaeger and Browne (1958) is one of variability of the seismicity pattern, a variability which is the more apparent because of the minor scale of the activity. At some times the whole of south-east Australia is quiet, and at others particular areas suffer series of earthquakes. Even in the areas of known seismic activity, there are fluctuations in the detailed pattern (Cleary 1967). Victoria certainly has an earthquake history of this variable character.

It may be instructive to draw these facts into the framework of a causal theory, which although speculative, will suggest fruitful further investigations. Forces directed to the northwest from the Tasman Sea are compressing the whole of south-east Australia. The crust is reacting mainly by movements on, and perhaps extensions of, suitably

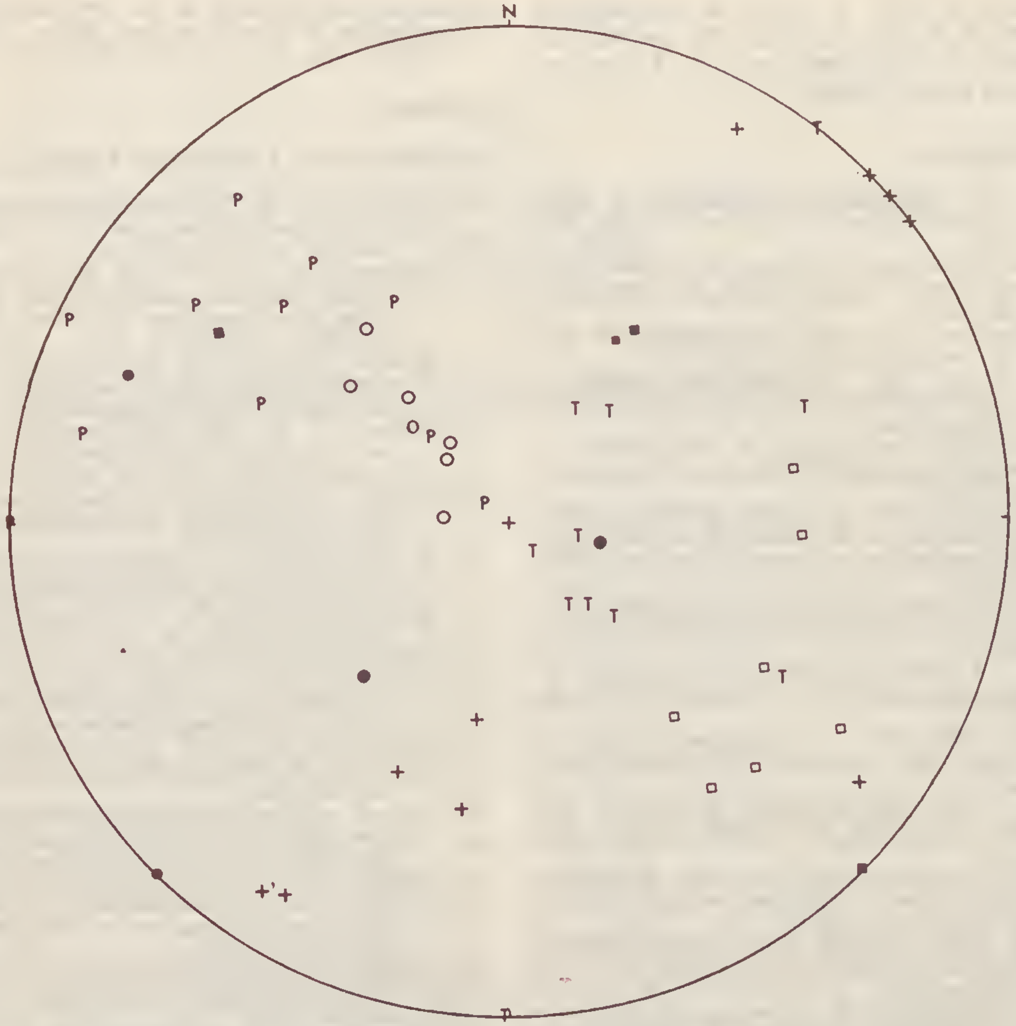

FIG. 6—Summary of south-eastern Australian focal mechanism solutions. Stereographic projection on the lower hemisphere.

oriented old faults. In Victoria, there are three main fault zones of this description. Movements between blocks tend to interfere with each other, and an earthquake may 'lock' a whole region in such a way that the main force field is bridged away through interlocking blocks to other parts of south-east Australia, leaving a core of relatively unstressed country which is free to relieve the previously imposed strain by small internal re-adjustments, which it does at a rate proportional to the remaining strain. The surrounding areas are thrown into a state of increased stress, and shocks in unusual locations may be experienced, until the 'lock' is broken. The force field then acts on the relaxed area, and most of the strain release is concentrated here for a time. The next stage could be that the movements begin again to interfere one with another, the area will 'work harden' so that a larger number of smaller earthquakes will occur in Victoria and the seismic activity will spread more uniformly over south-east Australia. In a few more years, enough seismicity studies will have been completed in south-east Australia, to make a thorough test of these speculations possible.

ACKNOWLEDGMENTS

The work reported here was done while I was in receipt of a post-graduate scholarship, and forms part of a thesis submitted to the Australian National University. The historical investigations were commenced when I was employed at the Bureau of Mineral Resources, to the Director of which I am indebted for permission to publish the information of Table 1. The work was initiated by Mr. H. A. Doyle, and I am also indebted to Professor J. C. Jaeger and Dr. J. R. Cleary for support and encouragement.

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APPENDIX

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